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PROPERTIES OF $b\bar{b}$ PRODUCTION AT THE TEVATRON [1]

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Abstract

We present a number of recent results obtained at the Fermilab Tevatron for $b\bar{b}$ production in $p\bar{p}$ interactions. The preliminary CDF and DØ measurements of the inclusive b-quark production cross section at $\sqrt{s} = 630$ GeV are compared with the UA1 results and the next-to-leading order QCD predictions. These results are used to compute the ratio of the cross sections at 630 GeV to 1800 GeV. The CDF results on the B meson differential cross section and Λ_b^0 baryon production and decay properties at $\sqrt{s} = 1800$ GeV are also presented.

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1 Introduction

The study of b-quark production in high energy hadronic interactions offers a crucial test of the perturbative quantum chromodynamics (QCD) description of heavy quark production [1, 2]. The cross section for b-quark production in $p\bar{p}$ collisions has been measured by the CDF and DØ collaborations at $\sqrt{s} = 1800$ GeV using various data samples [3, 4]. The cross sections agree in shape with the next-to-leading order (NLO) QCD predictions but are generally higher than the central predictions for the central rapidity region. However, they are compatible with the theoretical upper limit obtained when the uncertainties on the b-quark mass, m_b, and on the factorization and renormalization scale, μ, are taken into account.

At the end of 1995, the Tevatron was operating at a center-of-mass energy $\sqrt{s} = 630$ GeV, the energy at which the b-quark cross section was measured by the UA1 experiment [5]. These data offer a unique opportunity to measure the b-quark production cross section at two different energies using the same apparatus and to compare their ratio with the NLO QCD predictions. From a theoretical point of view, this ratio is less sensitive to a specific choice of parameters than the individual cross sections. From the experimental point of view, most of the systematic uncertainties affecting the cross section measurements should cancel in the ratio.

2 b-Quark Cross Sections at 630 and 1800 GeV

The DØ analysis of the 630 GeV data is based on events containing at least one muon, coming either from the direct b-quark semileptonic decay, $b \to \mu$, or the sequential decay, $b \to c \to \mu$. This study uses 342 ± 41 nb^{-1} of data recorded with a 2-level single muon trigger in the central part of the detector.

Events containing a muon candidate with a pseudorapidity $|\eta^\mu| < 0.8$ and a transverse momentum $4 < p_T^\mu < 10$ GeV/c were retained for further analysis. To remove zones of the DØ detector with lower muon chamber efficiency, the muon azimuthal angle was required to fall between 50° and 130°, corresponding to the top part of the detector. Valid muon candidates were also requested to be identified as a minimum ionizing particle in the calorimeter, and muon quality cuts were applied to remove badly measured tracks and combinatoric backgrounds. The muon scintillators were used to reduce the contamination from cosmic ray muons, removing muon candidates with a difference between the measured and the expected time of flight, ΔT_{tof}, greater than 12 ns. The cosmic ray background remaining in the final sample was determined by fitting a Gaussian plus a constant term to the ΔT_{tof} distribution. The fraction of cosmic rays, f_{bgd}, exhibits a strong p_T^μ dependence: f_{bgd} is less than 5% for $p_T^\mu < 5$ GeV/c but becomes larger than 80% when $p_T^\mu > 10$ GeV/c.

The inclusive muon cross section was obtained by the relation:

$$\frac{d\sigma^\mu}{dp_T^\mu} = \frac{N_\mu \cdot (1 - f_{bgd})}{\int \mathcal{L}dt \cdot \epsilon_\mu} \cdot f_{\text{unfold}} \;, \tag{1}$$

where N_μ is the number of selected muons, $\int \mathcal{L}dt$ is the integrated luminosity, and f_{unfold} is a correction factor that accounts for the smearing due to the muon momentum resolution. The global muon detection efficiency, ϵ_μ, was obtained with events generated with ISAJET Monte Carlo [6], simulated with GEANT and reconstructed in the same way as the data. This efficiency is approximately 10% with some p_T^μ dependence and was cross-checked whenever possible with the data. The relative systematic errors on the inclusive muon cross section are between 16 and 22%. Table 1 shows the contribution of the various factors to these systematic errors.

Table 1: Relative systematic errors on the various factors used to compute the inclusive muon cross section, the b-produced muon cross section, and the b-quark cross section (in %).

p_T^μ (GeV/c)	Δf_{bgd}	$\Delta\epsilon_\mu$	$\Delta\mathcal{L}$	Δf_{unfold}	$\Delta\sigma^\mu$	$\Delta\sigma_{\pi/K}$	Δf_b	$\Delta\sigma_b^\mu$	$\Delta(\sigma_b/\sigma_\mu)$	$\Delta\sigma^b$
4 – 5	0.4	9.6	12	4.1	15.9	49.7	10.5	53.2	10.6	54.2
5 – 6	1.3	8.4	12	5.8	15.8	34.9	12.3	40.2	12.4	42.1
6 – 8	3.0	8.0	12	8.0	16.8	19.0	12.3	28.2	13.5	31.3
8 – 10	10.4	9.4	12	11.6	21.8	19.0	8.3	30.1	13.8	33.1

The muon cross section for inclusive b-quark decays was extracted as follows:

$$\frac{d\sigma_b^\mu}{dp_T^\mu} = \left(\frac{d\sigma^\mu}{dp_T^\mu} - \frac{d\sigma_{\pi/K}^\mu}{dp_T^\mu}\right) \cdot f_b \ , \tag{2}$$

where $\frac{d\sigma_{\pi/K}^\mu}{dp_T^\mu}$ represents the differential cross section for pions and kaons decaying in flight into muons, and f_b is the fraction of muons from b-quark decays in the sample after subtraction of the π/K decays. Both elements were obtained using ISAJET.

To extract an inclusive b-quark production cross section from the muon spectrum, the method developed by UA1 and used by CDF and DØ at $\sqrt{s} = 1.8$ TeV was applied. The relation between the b-quark cross section and the experimental muon spectrum is given by

$$\sigma^b(p_T^b > p_T^{\min}) = \frac{1}{2}\,\sigma_b^\mu(p_T^{\mu 1}, p_T^{\mu 2})\,\frac{\sigma_{MC}^b}{\sigma_{MC}^\mu} \ , \tag{3}$$

where $\sigma_b^\mu(p_T^{\mu 1}, p_T^{\mu 2})$ is the b-produced muon cross section integrated over the interval $p_T^{\mu 1} < p_T^\mu < p_T^{\mu 2}$, σ_{MC}^b is the total inclusive b-quark cross section for $p_T^b > p_T^{\min}$ and rapidity $|\, y^b \,| < 1$, and σ_{MC}^μ is the cross section for production of b quarks that decay to muons within the p_T^μ interval and with $p_T^b > p_T^{\min}$. The factor $\frac{1}{2}$ yields the cross section average for b and $\bar{b}$ production from the measurement of μ^+ and μ^- data. The $\sigma_{MC}^b/\sigma_{MC}^\mu$ conversion factors were evaluated using the HVQJET MC event generator [7], based on MNR [2] for the $b\bar{b}$ event generation and ISAJET for initial and final state gluon radiation, followed by fragmentation and particle decay. The factors were computed using the MRSA' parton distribution function [8], together with the parameters $\Lambda_{\overline{MS}}^{(5)} = 152$ MeV, $m_b = 4.75$ GeV/c^2, $\mu = \mu_0 \equiv \sqrt{m_b^2 + (p_T^b)^2}$, and $Br(b \to \mu) = 0.105$. Table 1 summarizes the systematic uncertainties affecting the b-produced muon cross section and the b-quark cross section.

The CDF experiment has measured the relative b-quark production cross section as a function of the beam energy using events with a common signature at 630 and 1800 GeV [9]. Events containing muons associated with secondary vertices are selected in two samples of 0.46 pb^{-1} and 1.89 pb^{-1} of data collected at $\sqrt{s} = 630$ GeV and 1800 GeV, respectively. The muon candidates must have a transverse momentum greater than 6.2 GeV/c. The invariant mass resulting from the combination of this muon and the highest-p_T track (with $p_T > 1$ GeV/c) in a cone of radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.0$ around the muon direction must be between

1.5 GeV/c^2 and 5.3 GeV/c^2. The two particles are constrained to a common decay vertex and the transverse decay length in the μ-track momentum direction, L_{xy}, is required to be between 0.25 and 20 mm. Event yields of 164 ± 21 and 5617 ± 133 were obtained in the low and high energy samples, respectively. Taking into account the different acceptance for b events at the two energies ($A_{630}/A_{1800} = 0.62 \pm 0.04$), the ratio of cross sections is

$$\frac{\sigma^b(p_T^b > 9.5 \text{ GeV}/c, \mid y^b \mid < 1, \sqrt{s} = 630 \text{ GeV})}{\sigma^b(p_T^b > 9.5 \text{ GeV}/c, \mid y^b \mid < 1, \sqrt{s} = 1800 \text{ GeV})} = 0.193 \pm 0.025\,(stat.) \pm 0.023\,(syst.)\ , \quad (4)$$

where the systematic error is dominated by the uncertainty in the integrated luminosity at 630 GeV. The b-quark cross section for $\sqrt{s} = 630$ GeV was determined from this ratio and the cross sections measured by CDF for $\sqrt{s} = 1800$ GeV in the channel $b \to J/\psi X$ [10].

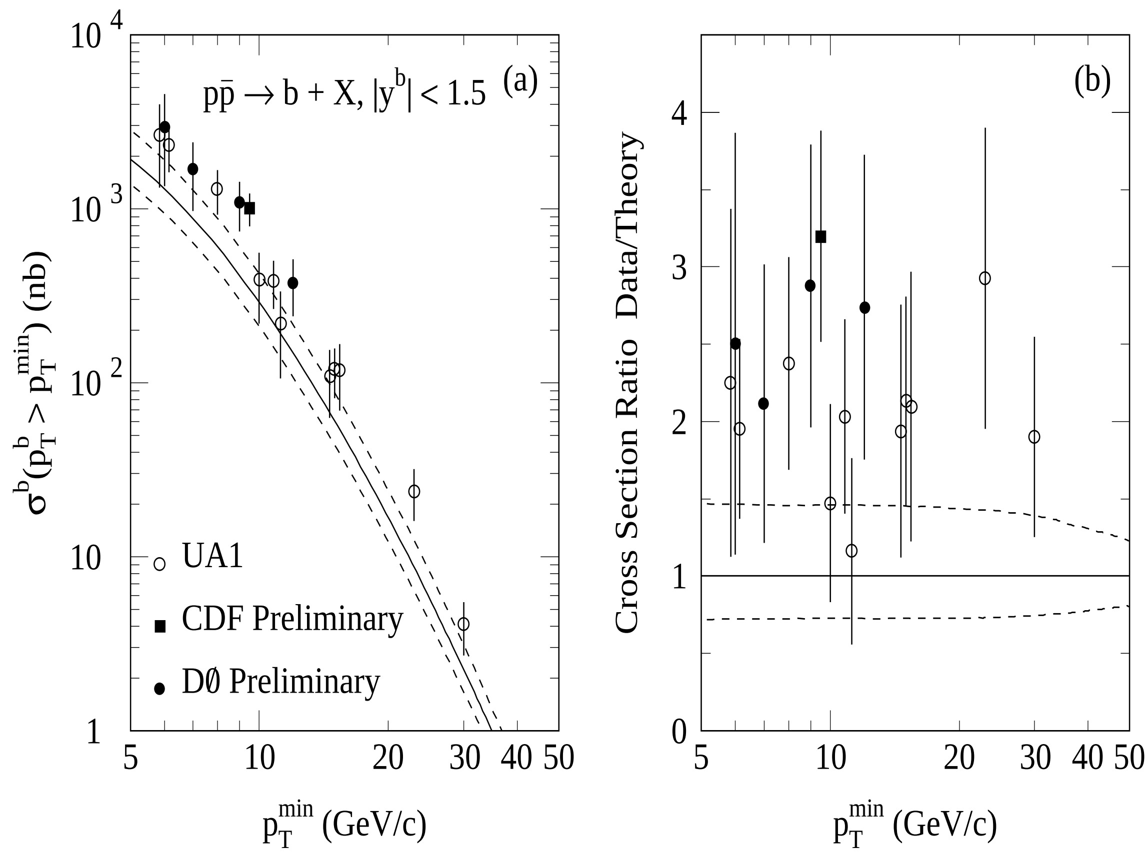

Figure 1: The b-quark production cross sections measured by CDF (square), DØ (closed circles) and UA1 (open circles) at 630 GeV compared with the NLO QCD predictions (see text).

The b-quark production cross sections obtained by the CDF and DØ experiments are shown in Fig. 1a, together with the UA1 results [5]. The CDF and DØ cross sections, measured for $\mid y^b \mid < 1$, were scaled by a factor obtained with MNR to correspond to the same rapidity interval as UA1, $\mid y^b \mid < 1.5$. The NLO QCD prediction, shown by the solid line, is based on the MNR calculation [2] using the MRSA' structure function with $\Lambda^{(5)}_{\overline{MS}} = 152$ MeV, $m_b = 4.75$

GeV/c^2 and $\mu = \mu_0$. The dashed curves show the theoretical uncertainties obtained by varying m_b between 4.5 and 5 GeV/c^2, and μ between $\mu_0/2$ and $2\mu_0$. The ratio of the measured cross sections to the theoretical expectations is shown in Fig. 1b.

The ratios of the cross sections obtained at 630 and 1800 GeV are presented in Fig. 2. The horizontal inner and outer bars show the statistical and the total errors affecting these ratios, respectively. These results are in good agreement with the NLO QCD predictions, computed in the same way as in Fig. 1. The total errors on the DØ ratios are large because the ratios were obtained by dividing the absolute cross sections independently measured at 630 GeV and 1800 GeV [3], assuming that only the systematic errors on the integrated luminosity and the $\sigma^b_{MC}/\sigma^\mu_{MC}$ conversion factors were correlated between each measurement. Future analyses should reduce the errors on the ratio.

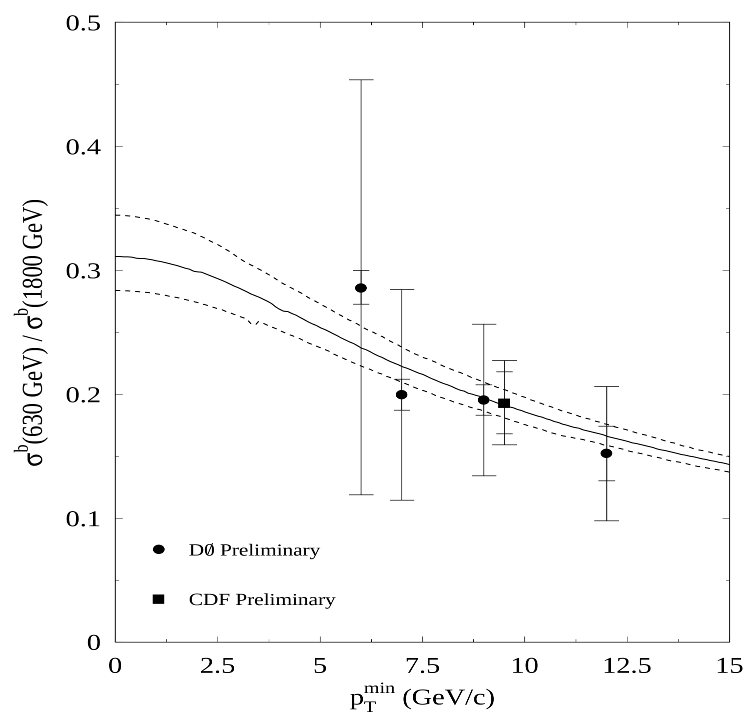

Figure 2: Ratio of b-quark production cross sections at 630 GeV to 1800 GeV.

3 B Hadron Production at 1800 GeV

The CDF collaboration has recently performed a new measurement of the B meson differential cross section using the exclusive decays $B^\pm \to J/\psi + K^\pm$ where $J/\psi \to \mu^+\mu^-$. These results were obtained from a sample of 54.4 pb^{-1} of data collected during 1994–1995.

The selection of $B^\pm$ candidates begins by identifying $J/\psi \to \mu^+\mu^-$ candidates where both muons have $p_T > 2.0$ GeV/c and an invariant mass within 4σ of the known J/ψ mass. The J/ψ and a $K^\pm$ candidate (with $p_T > 1.25$ GeV/c) are fit to a common vertex and the proper decay length of the B candidate is required to be greater than 100 μm. Finally, the B candidates must satisfy $5.2 < m(\mu^+\mu^- K) < 5.6$ GeV/c^2 and have $p_T > 6$ GeV/c.

The $B^{\pm}$ differential cross sections were combined with previous measurements [11] based on 19.3 pb^{-1} of 1992–1993 data using the exclusive decays $B^{\pm} \rightarrow J/\psi + K^{\pm}$ and $B^0 \rightarrow J/\psi + K^{*0}$, where $J/\psi \rightarrow \mu^+\mu^-$ and $K^{*0} \rightarrow K^+\pi^-$. The combined differential cross section is found to be consistent in shape with the NLO QCD prediction computed with MNR, the MRSDØ proton structure functions and the Peterson parameterization for fragmentation, using a value of the fragmentation parameter of 0.006. As shown in Fig. 3, the measurement is a factor $2.1 \pm 0.2 \pm 0.3$ above the central theoretical value obtained with $m_b = 4.75$ GeV$/c^2$ and $\mu = \mu_0$.

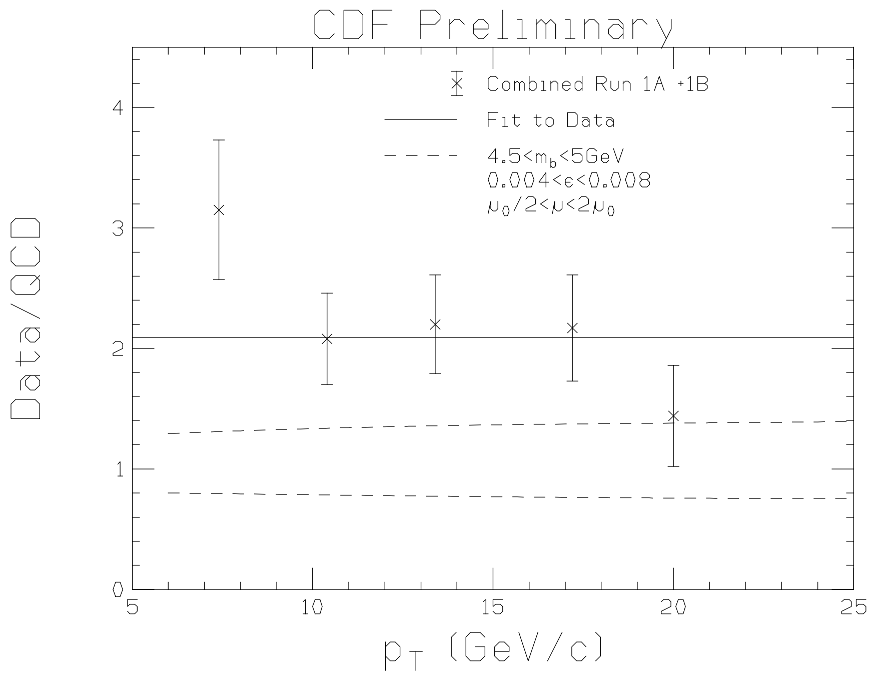

Figure 3: Ratio of the B meson differential cross section to the theoretical prediction.

Observation of the Λ_b^0 production at the Tevatron has been reported by the CDF collaboration using the exclusive decay $\Lambda_b^0 \rightarrow J/\psi\Lambda$ [12]. The events could be used to determine the Λ_b^0 cross section times branching fraction $\sigma(\bar{p}p \rightarrow \Lambda_b^0 X)\, Br(\Lambda_b^0 \rightarrow J/\psi\Lambda)$ but, in order to minimize several systematic uncertainties, CDF has measured the ratio of production cross section times branching ratio for the $\Lambda_b^0 \rightarrow J/\psi\Lambda$ and $B^0 \rightarrow J/\psi K_s^0$ decays, where $J/\psi \rightarrow \mu^+\mu^-$, $\Lambda \rightarrow p\pi^-$, and $K_s^0 \rightarrow \pi^+\pi^-$.

Using a sample of 110 pb^{-1} of data collected at 1.8 TeV, 7.8 ± 3.4 Λ_b^0 and 57.6 ± 8.7 B^0 candidates were identified, giving the ratio

$$\frac{\sigma(\bar{p}p \rightarrow \Lambda_b^0 X)\, Br(\Lambda_b^0 \rightarrow J/\psi\Lambda)}{\sigma(\bar{p}p \rightarrow B^0 X)\, Br(B^0 \rightarrow J/\psi K_s^0)} = 0.27 \pm 0.12\,(stat.) \pm 0.05\,(syst.), \tag{5}$$

valid for $p_T(\Lambda_b^0, B^0) > 6$ GeV$/c$ and $\mid \eta(\Lambda_b^0, B^0) \mid < 0.6$. Assuming $\sigma_{\Lambda_b^0}/\sigma_{B^0} = 0.1/0.375$ and $Br(B^0 \rightarrow J/\psi K_s^0) = 3.7 \times 10^{-4}$, CDF obtains the branching ratio

$$Br(\Lambda_b^0 \rightarrow J/\psi\Lambda) = [3.7 \pm 1.7\,(stat.) \pm 0.7\,(syst.)] \times 10^{-4}. \tag{6}$$

4 Conclusions

We have presented various measurements of b-quark and B hadron production cross sections in $p\bar{p}$ collisions performed by the CDF and DØ experiments at the Tevatron. These measurements agree in shape with the NLO QCD calculation but are larger than the central value of these predictions. These trends are observed at 630 GeV and 1800 GeV but the ratio of the b-quark production cross sections at these two energies is compatible with the expectations. The B meson differential cross section as measured by CDF at $\sqrt{s} = 1.8$ TeV is a factor $2.1 \pm 0.2 \pm 0.3$ above the NLO QCD prediction. The ratio of production cross section times branching fraction measured by CDF for the $\Lambda_b^0 \to J/\psi\Lambda$ and $B^0 \to J/\psi K_s^0$ decays is found to be $\frac{\sigma(\bar{p}p\to \Lambda_b^0 X)\, Br(\Lambda_b^0\to J/\psi\Lambda)}{\sigma(\bar{p}p\to B^0 X)\, Br(B^0\to J/\psi K_s^0)} = 0.27 \pm 0.12\,(stat.) \pm 0.05\,(syst.)$.

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